

# PSR B1257+12: a quark star with planets?

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**Abstract.** A recent observation has shown that PSR B1257+12 could have quite small X-ray emitting area, only about  $2000 \text{ m}^2$ , which is more than three orders smaller than the canonical polar cap size. We suggest here that PSR B1257+12 could be a low-mass quark star with radius of  $R \simeq 0.6 \text{ km}$  and mass of  $M \simeq 3 \times 10^{-4} M_{\odot}$ . Such a low-mass quark star system may form in an accretion induced collapse process or a collision process of two quark stars.

**Keywords:** Pulsars, Neutron stars

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## INTRODUCTION

The first three extrasolar planets [1] was discovered around a millisecond pulsar, PSR B1257+12, with spin period of  $P = 6 \text{ ms}$ . Dispersion measure shows a distance of about  $500 \text{ pc}$  to pulsar, and X-ray spectrum reveals a hydrogen column density of  $N_{\text{H}} = 3 \times 10^{20} \text{ cm}^2$  [2]. The parameters of the three planets are listed in Table 1. A recent

**TABLE 1.** Parameters of PSR B1257+12's planets: orbital period  $P_{\text{orb}}$ , mass  $m_{\text{p}}$ , orbital radii  $a_{\text{p}}$  [3], mass from this work  $m_{\text{p,new}}$ , and orbital radii from this work  $a_{\text{p,new}}$ .

Planet	$P_{\text{orb}}$ (day)	$m_{\text{p}}$ ( $M_{\text{earth}}$ ) *	$a_{\text{p}}$ (AU) *	$m_{\text{p,new}}$ ( $M_{\text{earth}}$ ) †	$a_{\text{p,new}}$ (AU) †
A	25.3	0.02	0.19	0.000072	0.011
B	66.5	4.3	0.36	0.016	0.022
C	98.2	3.9	0.46	0.014	0.027

\* assuming a central pulsar of  $M = 1.4 M_{\odot}$ .

† this work, assuming a central pulsar of  $M = 3 \times 10^{-4} M_{\odot}$ , see text.

observation has, however, shown that the millisecond pulsar B1257+12 could have very small X-ray emitting area, only about  $2000 \text{ m}^2$  [2], which is remarkably smaller than the expected value assuming a pulsar with  $R \sim 10 \text{ km}$ . The observation covered  $20 \text{ ks}$  and received  $25$  photons. Both power law and blackbody models are acceptable. The blackbody fitting gives:  $kT \simeq 0.22 \text{ keV}$  and projected emitting area  $A \simeq 2000 \text{ m}^2$ . The bolometric luminosity is  $2L_{\text{bol}} \sim 3 \times 10^{29} \text{ ergs s}^{-1}$  [2].

For a pulsar with  $R = 10 \text{ km}$  and  $P = 6 \text{ ms}$ , the polar cap area is  $1.1 \times 10^7 \text{ m}^2$ , nearly four orders higher than the fitted area ( $A \simeq 2000 \text{ m}^2$ ). In this article, we will demonstrate that this discrepancy could be explained by assuming that PSR B1257+12 is a low-mass quark star (QS, for a general review, please see [4] in this proceedings). The precessing radio pulsar, PSR B1828-11, could also be a low-mass QS torqued by a quark planet orbiting around [5]. We discuss the possibility of planet formation under this new scenario, that differs from the models in which PSR B1257+12 is a normal neutron star of  $M = 1.4 M_{\odot}$ .

## A LOW-MASS QUARK STAR MODEL

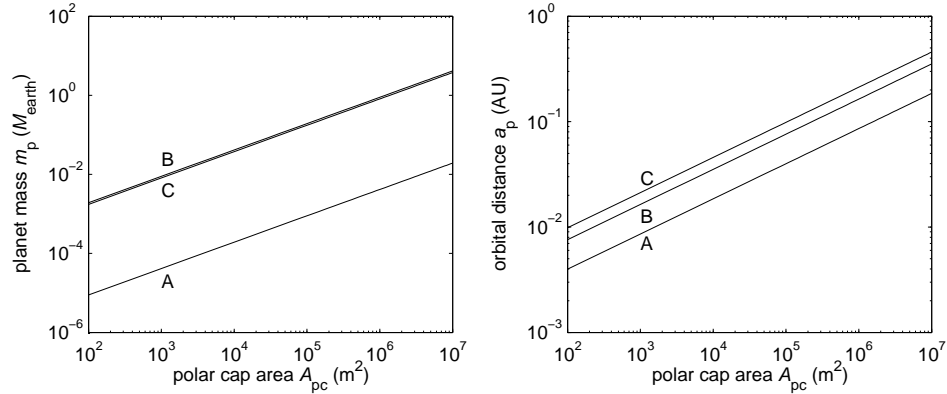
For a pulsar of  $R = 10$  km and  $P = 6$  ms, the theoretical value of the polar cap area is  $A_{\text{pc,th}} \simeq 2\pi^2 R^3 / (cP) = 1.1 \times 10^7 \text{ m}^2$  (where  $c$  is the light speed), which is  $\sim 5000$  times larger than the observation. We consider that PSR B1257+12 is a low-mass quark star. Its radius is  $R_{\text{new}} = 0.6$  km to fit the observed emitting area  $A \sim 2000 \text{ m}^2$ . Hence, the mass of the quark star is  $M_{\text{new}} = 3 \times 10^{-4} M_{\odot}$ .

Consequently, the planet's parameters such as the masses and distances to the central pulsar ( according to the third Keplerian law) would be changed,

$$\frac{m_{\text{p,new}}}{m_{\text{p}}} \simeq \left( \frac{R_{\text{new}}}{10 \text{ km}} \right)^2 = \left( \frac{A}{1.1 \times 10^7} \right)^{2/3}, \quad \frac{a_{\text{p,new}}}{a_{\text{p}}} \simeq \frac{R_{\text{new}}}{10 \text{ km}} \simeq \left( \frac{A}{1.1 \times 10^7} \right)^{1/3}.$$

Through the third Keplerian law, we can obtain that  $a_{\text{p}} \propto R$ . However, the orbital radius of the pulsar ( $a_{\text{M}}$ ) should not depend on  $R$  (or  $A$ ), so as to have the same time residue of pulse TOA (time of arrival) as the  $M = 1.4 M_{\odot}$  case. So we have  $m_{\text{p}} \propto R^2$ .

The new values,  $m_{\text{p,new}}$  and  $a_{\text{p,new}}$ , are presented in Table 1. We also show in Fig. 1 the the masses ( $m_{\text{p}}$ ) and the orbital radii ( $a_{\text{p}}$ ) of the planets as functions of polar cap area ( $A_{\text{pc}}$ ).



**FIGURE 1.** The masses and orbital distances of planets as functions of polar cap area.

Small star radius would induce smaller potential drop  $\Phi$  in the polar cap region. The potential drop  $\Phi$  should be larger than a critical value  $\Phi_{\text{c}} (\sim 10^{12} \text{ V})$  in order to make a quark star manifest as a radio pulsar [6, 7]. Considering the effects of inclination angle [8], the potential drop  $\Phi$  in the polar cap region be as larger than  $10^{12} \text{ V}$  if the inclination angle  $\alpha$  is between  $10^\circ$  and  $60^\circ$ .

## DISCUSSION

How the central low-mass quark star form? How the planets form? We propose two possible scenarios for this pulsar-planets system:

- A low-mass quark star and three quark planets. Such a system may form after collision of quark stars, and the quark planets could also be ejected during supernovae explosion of quark star formation [9].

- A low-mass quark star and three normal planets. Such a system may form through accretion induced collapse (AIC) process of white dwarfs [10] or a quark nova explosion [11]. The planets could probably form in the fallback disk that forms after the collapse.

The low-mass quark star model has advantage for planet formation since it has low X-ray luminosity (the disk is cool and the effect of planet evaporation is thus weak). The cooling time scale for the central star is  $\tau_{\text{cool}} \sim V/\mathcal{A} \sim R^3/R^2 \sim R$ , where  $V$  is the stellar volume and  $\mathcal{A}$  is the stellar surface area. A low-mass quark star has smaller radius and cools more rapidly than a normal neutron star of  $R = 10$  km. So the X-ray luminosity decrease in a shorter time scale. This may make it easier for disk to form and hence planets formation.

The observation could be fitted by both blackbody and power law function [2]. Due to the small number of photons, it is hard to distinguish these two type of models. We assume that the emission is blackbody in our calculation. If there is power law component in the emission, the blackbody part would be smaller. Thus, the central star should be even smaller.

## SUMMARY

Pulsar 1257+12 could possibly be a low-mass quark star (with three planets) of  $R = 0.6$  km if its X-ray luminosity is from the polar caps. In this case the mass of the planets would be smaller by a factor of 0.0036. The planets around the low-mass quark star may form in the fallback disk after an AIC process/a quark nova explosion, through a collision of quark stars, or as the ejecta during quark star formation.

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